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Analysis of Buoyant Surface Jets

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16. ABSTRACT

To obtain improved prediction of heated plume characteristics from a surface jet, an integral analysis computer model was modified and a comprehensive set of field and laboratory data available from the lieterature was gathered, analyzed, and correlated for estimating the magnitude of certain coefficients that are normally introduced in these analyses to achieve closure. The parameters so estimated include the coefficients for entrainment, turbulent exchange, drag, and shear. Since there appeared considerable scatter in the data, even after appropriate subgrouping to narrow the influence of various flow conditions on the data, only statistical procedures could be applied to find the best fit. This and other analyses of its type have been widely used in industry and government for the prediction of thermal plumes from steam power plants. Although the present model has many shortcomings, a recent independent and exhaustive assessment of such predictions revealed that in comparison with other analyses of tis type the present analysis predicts the field situations more successfully.

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Analysis of Buoyant Surface Jets

To obtain improved prediction of heated plume characteristics from a surface jet, an integral analysis computer model was modified and a comprehensive set of field and laboratory data available from the literature was gathered, analyzed, and correlated for estimating the magnitude of certain coefficients that are normally introduced in these analyses to achieve closure. The parameters so estimated include the coefficients for entrainment, turbulent exchange, drag, and shear. Since there appeared considerable scatter in the data, even after appropriate subgrouping to narrow the influence of various flow conditions on the data, only statistical procedures could be applied to find the best fit. This and other analyses of its type have been widely used in industry and government for the prediction of thermal plumes from steam power plants. Although the present model has many shortcomings, a recent independent and exhaustive assessment of such predictions revealed that in comparison with other analyses of its type the present analysis predicts the field situations more successfully.

Introduction

Various mathematical models of heated surface jets are available to predict two- and three-dimensional plume configurations. Two widely accepted methods are used for solving the equations in these models, the integral analysis approach and the differential numerical analysis methods. The latter approach, while capable of greater generality, is considerably more costly and due to limited funds and resources was excluded from further consideration for this work. However, a certain degree of generality of results is retained by considering only three-dimensional plume models herein.

Comprehensive reviews of thermal plume models are presented in references [4 , 9].[1] Among the three-dimensional surface jet models seriously considered is one by Stolzenbach and Harleman (MIT Model) [3, 5], another by Prych [1] and the third model by Stefan, et al. [10]. It is outside the scope of this peper to discuss in detail results of all experiments on the three models during our attempt to provide a working program. The MIT model, despite its many fine features, runs into considerable computational difficulties. Prych's model is the result of a reasonably successful attempt to remove some of these difficulties from MIT's model. Stefan's model was written for the developed zone alone and thus can't be compared with others directly. Even though it includes wind effects absent in the other two, it ignores the hydrostatic pressure in the longitudinal direction.

In general, the MIT and Prych models yield comparable predictions [1]. The greatest deviation between the predictions of both models and data is in plume width. Both models overestimate the plume width except near the source or at high Froude numbers. The magnitude of the over predictions can best be assessed from reading references [3, 9].

Modifications are introduced in Prych's model to make it better agree with existing data. These are discussed in the following.

Theoretical Analysis

The analysis due to Prych [1] is given here in an abbreviated form. All lengths have been normalized by H_0, velocities by U_0, excess temperatures by ΔT_0, and densities by ρ_0. All terms have been defined in the Nomenclature. The temperature and velocity profiles are assumed to be Gaussian such that

$$T_r = T \exp(-n^2/B^2) \cdot \exp(-Z^2/H^2) \tag{1}$$

$$U_r = U \exp(-n^2/B^2) \cdot \exp(-Z^2/H^2) + V \cos\theta \tag{2}$$

where n and Z are distances perpendicular to the plume center line in the lateral and vertical directions, respectively. T and U are the center-line excess temperature and velocity, respectively. Fig. 1 shows the coordinate system used.

The energy, volume, and momentum fluxes across the plume at an arbitrary cross section are calculated in terms of center-line velocity, center-line temperature, plume characteristic width, B, and plume characteristic depth, H. Accordingly, the volume flux is

$$Q = \int\int U_r\, dn\, dZ \simeq \pi BH\left(\frac{U}{2} + V\cos\theta\right) \tag{3}$$

where the limits of integration for $V \cos\theta$ are taken as the bottom half of the region

$$\left(\frac{n}{\sqrt{2}B}\right)^2 + \left(\frac{Z}{\sqrt{2}H}\right)^2 \leq 1 \tag{4}$$

Solving (3) for U yields

[1] Numbers in brackets designate References at end of paper.

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$$U = 2\left(\frac{Q}{\pi BH} - V\cos\theta\right) \tag{5}$$

The heat flux, J, is

$$J = \int\int U_r T_r \, dn dZ \simeq \frac{\pi}{2} TBH\left(\frac{U}{2} + V\cos\theta\right) = \frac{QT}{2} \tag{6}$$

The momentum flux, M, is

$$M = \int\int U_r^2 \, dn dZ \simeq \pi BH\left(\frac{U}{2} + V\cos\theta\right)^2 \tag{7}$$

$$M = \frac{Q^2}{\pi BH} \tag{8}$$

The quantities dQ/ds, dT/ds, and dM/ds are calculated from the conservation equations. dQ/ds is assumed to be the sum of contributions of jet entrainment and ambient turbulent mixing in the horizontal and vertical directions.

The horizontal jet entrained fluid is

$$\left.\frac{dQ}{ds}\right|_{j,h} = \sqrt{\pi} HE_0(U^2 + V^2\sin^2\theta)^{1/2} \tag{9}$$

where E_0 is an entrainment coefficient.

The vertical jet entrainment fluid is

$$\left.\frac{dQ}{ds}\right|_{j,v} = 2\int_0^{\sqrt{2}B} E_0 f(R_i)\,[U^2\exp(-2n^2/B^2) + V^2\sin^2\theta]^{1/2}\,dn \tag{10}$$

The function $f(R_i) = [\exp(-5R_i) - 0.0183]/0.982$ is a curve fit to the experimental data of Ellison and Turner [7] with respect to the local Richardson number R_i.

The effective entrainment due to ambient turbulent mixing, according to Prych, is

$$\left.\frac{dQ}{ds}\right|_{a,h} = 11.0\frac{H}{B}\frac{\epsilon_h}{U_0 H_0} \tag{11}$$

$$\left.\frac{dQ}{ds}\right|_{a,v} = 11.0\frac{B}{H}\frac{\epsilon_v}{U_0 H_0} f(R_i') \tag{12}$$

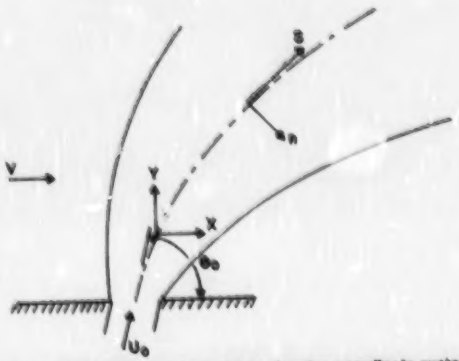

Fig. 1 Plan view of surface plume showing coordinate system

and ϵ_h and ϵ_v are the horizontal and vertical turbulent diffusion coefficients, respectively.

The change in heat flux along the plume is

$$\frac{dJ}{ds} = -2\int_0^\infty KT_r\,dn = \sqrt{\pi}KTB \tag{13}$$

where K is the dimensionless surface heat exchange coefficient. Subtituting (6) into (13) yields

$$\frac{dT}{ds} = \frac{-T}{Q}\left(2\sqrt{\pi}KB + \frac{dQ}{ds}\right) \tag{14}$$

The net forces on the plume are balanced by the change in momentum flux. The forces considered important are: (a) internal pressure forces due to buoyancy, (b) form drag due to ambient current, and (c) interfacial shear forces.

The pressure forces are found by determining the excess pressure due to buoyancy as a function of depth and then integrating the pressure over the vertical cross section of the plume. Thus, the normalized pressure force is

Nomenclature

A = aspect ratio $2B_0/H_0$
B = local characteristic width of jet = $\sqrt{2}\sigma_n$
B_0 = half width of outlet
$B_{1/2}$ = plume half width = $1.177\,\sigma_n$
C_D = form drag coefficient
C_F = interfacial shear drag coefficient
c = celerity of a density front
C_s = spreading coefficient
E_h = dimensionless horizontal eddy diffusion coefficient ϵ_h/U_0H_0
E_0 = entrainment coefficient
E_v = dimensionless vertical eddy diffusion coefficient ϵ_v/U_0H_0
F_0 = densimetric Froude number at outlet, $U_0/\sqrt{g'H_0}$
g = acceleration due to gravity
g' = reduced gravitational acceleration, $g\Delta\rho/\rho_a$
H = local characteristic thickness of jet $\sqrt{2}\sigma_z$
H_0 = depth of outlet
J = heat flux
K = dimensionless surface heat transfer coefficient
M = momentum flux
n = curvilinear coordinate horizontal and normal to jet center line
P = normalized hydrostatic pressure force
Q = mass flux
R = velocity ratio V/U_0
R_i = local Richardson number defined by $R_i = \sqrt{2}H^2T_r(n,0)/[F_0^2[U^2\exp(-2n^2/B^2) - V^2\sin^2\theta]]$
R_i' = bulk Richardson number defined by $R_i' = \sqrt{2}HT/[F_0^2(U + V\cos\theta)]$
s = curvilinear coordinate along jet center line
S_i = distance from outlet to end of initial zone
T = dimensionless center line excess temperature $\Delta T_c/\Delta T_0$
ΔT_c = excess water surface temperature on jet center line
ΔT_0 = discharge excess water temperature
T_r = local excess temperature in plume cross section defined in equation (1)
U = excess jet velocity on jet center line
U_0 = discharge velocity from outlet
U_r = local velocity in plume cross section defined in equation (2)
V = ambient current velocity
X = rectilinear coordinate parallel to ambient current
Y = rectilinear coordinate, horizontal and perpendicular to X
Z = coordinate in vertical direction
$\Delta\rho$ = difference between outlet and ambient water densities
ϵ = turbulent diffusion coefficient
ϵ_h, ϵ_v = ambient turbulent diffusion coefficient for horizontal and vertical directions
θ = angle between X axis and plume center line
ρ = fluid density
σ_n, σ_z = standard deviation of Gaussian profile in n- and z-directions

Subscripts

a = ambient conditions
c = center-line value at surface
h = horizontal
i = refers to variables at end of development zone
0 = discharge conditions
r = perpendicular to s in n- and Z-directions
v = vertical

$$P = \frac{1}{F_0^2} \int\int \left\{ \int_{-\infty}^{Z} T_r dZ \right\} dn\,dZ = \sqrt{\pi}\, TH^2B/2F_0^2 \qquad (15)$$

The form drag acting normal to the plume center line is assumed similar to the drag on a solid body. The interfacial shear forces are assumed to be similar to turbulent flow over a flat surface with a boundary layer thickness of $\sqrt{2}H$.

The change in momentum flux includes the effects of the momentum of the entrained ambient fluid, $V dQ/ds$, which acts in the X-direction. Equating the forces to the change in momentum flux in the X- and Y-direction yields

$$\frac{d}{ds}(M + P)\cos\theta = SF_X + F_D \sin\theta + V\frac{dQ}{ds} \qquad (16)$$

$$\frac{d}{ds}(M + P)\sin\theta = SF_Y - F_D \cos\theta \qquad (17)$$

where F_D is the drag force and SF_X and SF_Y are the X and Y components of the interfacial shear force. Using equations (8) and (15) for M and P, multiplying (16) by $-\sin\theta$, (17) by $\cos\theta$, and combining, yields an expression for the change in flow direction

$$\frac{d\theta}{ds} = \frac{SF_Y\cos\theta - SF_X\sin\theta - F_D - V\sin\theta\,(dQ/ds)}{\dfrac{Q^2}{\pi BH} + \dfrac{\sqrt{\pi}}{2F_0^2}TH^2B} \qquad (18)$$

Differentiating M and P, multiplying (16) by $\cos\theta$ and (17) by $\sin\theta$, and combining yields

$$\frac{dH}{ds} = [SF_Y\sin\theta + SF_X\cos\theta + (V\cos\theta - 2Q/\pi BH)(dQ/ds) - (\sqrt{\pi}\,BH/2F_0^2)(dT/ds) + (Q^2/\pi B^2H^2 - \sqrt{\pi}\,H^2T/2F_0^2)(dB/ds)] \times [\sqrt{\pi}\,THB/2F_0^2 - Q^2/\pi BH^2]^{-1} \qquad (19)$$

It should be noted that this expression for change in depth is undefined when the denominator becomes zero.

Momentum in the lateral direction is included only indirectly through lateral spreading. It is assumed that the contributions to spreading by nonbuoyant horizontal jet mixing and buoyancy are independent of one another.

The nonbuoyant spreading is found by writing equation (19) without the buoyancy terms (any terms containing F_0) and by assuming that

$$\left(\frac{dB/ds}{dH/ds}\right)_{nb} = (B/H)(dQ/ds)_h/(dQ/ds)_v$$

where $(dQ/ds)_h$ and $(dQ/ds)_v$ are the horizontal and vertical entrainment rates. Accordingly,

$$\left(\frac{dB}{ds}\right)_{nb} = \frac{SF_Y\sin\theta + SF_X\cos\theta + \left(V\cos\theta - \dfrac{2Q}{\pi BH}\right)\dfrac{dQ}{ds}}{-(Q^2/\pi B^2H)[(dQ/ds)_v/(dQ/ds)_h + 1]} \qquad (20)$$

The buoyant spreading function used by Prych was based on the analysis of an immiscible film, such as oil spreading without friction over water. This ignores the shear interaction between the fluid systems as well as the variation in fluid densities at the interface. Furthermore, the fluid particles were assumed to move with a velocity equal to the velocity caused by an abrupt density front. When applied to a heated plume, these assumptions lead to an overprediction of plume width compared with the actual spreading.

In a separate analysis of a buoyant spreading of a pool of warm water, Koh and Fan [6] accounted for the interfacial shear but ignored the actual entrainment of the cool water. They found that near the source the spreading velocity and the fluid velocity used by Prych are the same, i.e.,

$$V_n^2 = c^2 \sim g'h$$

where H is the local depth of the buoyant pool. However, far away from the source where the shear forces become very important, the fluid front velocity is

$$V_n^2 \sim \frac{g'H}{(\epsilon/H\rho)}(H/B)$$

where $g'H$ is proportional to c^2, $(\epsilon/H\rho)$ is proportional to the shear velocity and H/B is the ratio of the local pool depth to its width. If interpreted in terms of plume spread, this finding implies that spreading velocity is inversely proportional to the local aspect ratio of the plume.

The appearance of the local aspect ratio in the expression for the plume velocity offers an intuitively appealing ground for assuming

$$V_n^2 \sim (g'H)(H/B)$$

This can also be explained as follows. The lower density of the plume causes it to rise slightly about the free surface of the surrounding water. The height of rise at any point is proportional to the local vertical density difference between the plume and the ambient and the depth of the plume at this point. Since both the density difference and depth of the plume decrease from the center to the edge, this height varies from a maximum at the center to zero at the edge, causing the plume to spread in that direction. The spreading rate due to buoyancy is related to the slope of this free surface. Since the height of rise at the center is proportional to $g\Delta\rho_c H/\rho$, the slope of the free surface and thus the spreading rate is a function of $g\Delta\rho_c H/\rho B$.

As a result of the foregoing discussion the buoyant spreading developed in this study is

$$\left(\frac{dB}{ds}\right)_b = \frac{C_s}{\left(\dfrac{B}{H}F^2 - 1\right)^{1/2}} \qquad (21)$$

where C_s is an imperical spreading coefficient and F is the local Froude number defined by $F = F_0Q/(TH^2B^2\pi^{3/2})^{1/2}$.

The preceding equations are sufficient to perform a step-wise integration along the plume. From the local conditions of the plume, dQ/ds and then dT/ds, $d\theta/ds$, dB/ds, and finally dH/ds can be calculated in that order. These derivatives are integrated step-wise along the plume trajectory to give local values of X, Y, T, H, B, θ, and Q.

To start the integration within the developed zone where the foregoing analysis is valid, starting conditions must be calculated. These are determined by a simplified analysis of the development zone.

The length of the development zone is based on experiments made in a still tank at the Corvallis Environmental Research Laboratory [11]. It was found to be approximately:

$$S_i = 5.4\left(\frac{A^2}{F_0}\right)^{1/3} \qquad (22)$$

For details of the development zone calculation, the reader is referred to reference [11]. The work by Stefan, et al. [15] provides more up-to-date information necessary for improved predictions in the development zone.

Fitting the Model with Data

Reference [2] provides a comprehensive set of data that is a good representation of available experiments both in the field and laboratory. The data provide a wide range of plume conditions with which one can test and accordingly adjust numerous analytical functions of the plume model. The plume model contains a number of free variables such as entrainment coefficient E_0, turbulent exchange coefficients E_h, E_v, drag coefficient C_D, and shear coefficient C_F. The magnitudes of these coefficients must be prespecified so that the model produces the best fit with the measured plume characteristics.

To accomplish this task, the following procedure is adopted: (a) Data for plume characteristics are subgrouped with a narrow range of the experimental scaling parameters. These parameters are the current ratio, R, the discharge densimetric Froude number, F_0, the jet aspect ratio, A, and the angle of discharge, θ_0. Each subgroup contains data from several sources, thus providing considerable realism with respect to possible experimental scatter and variations in

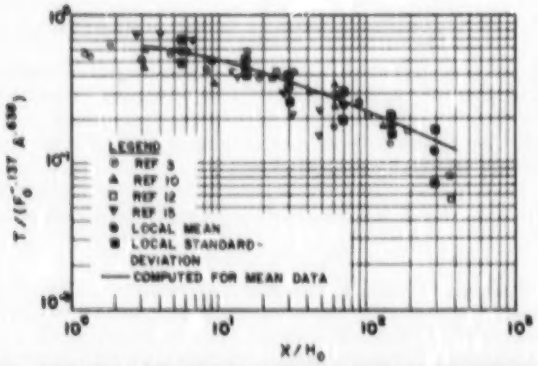

Fig. 2 Correlation of selected field and laboratory surface plume temperature data at negligible ambient current as compared to calculated values

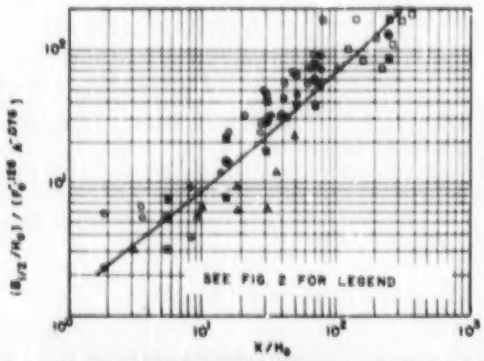

Fig. 3 Correlation of selected field and laboratory width data at negligible ambient current as compared to calculated values

experimental parameter scales. The choice of a narrow range in certain experimental parameters was dictated by the desire to obtain as strong a correlation of the data within a given subgroup as possible. (*b*) For each subgroup, the range and mean of all experimental parameters are determined. (*c*) The data are correlated using dimensional analysis with the scaling parameters as variables and multiple regression methods separately for each subgroup following the procedure outlined in [2]. (*d*) The measured plume characteristics are plotted against dimensionless axial distance using the correlation results. (*e*) Finally, the analytical program is used to calculate the plume characteristics in each subgroup for the mean of the experimental parameters R, F, A, and θ_0. Agreement between the calculated characteristics and the data mean is sought by adjusting one or more of the model coefficients E_0, E_h, E_v, C_D, C_F, and C_S. This process is repeated for several subgroups, adjusting in each trial one or more coefficients until best fits are obtained to plume characteristics for all subgroups.

The correlations obtained by this method have been used in ordinates in the figures of this paper. It should be pointed out that these correlations of each data subgroup are useful mainly for the mean data in that subgroup. They are not universal correlations and cannot be used outside the data range they represent.

Turbulent Exchange Coefficients, E_h, E_v. It should be understood that the turbulent exchange coefficients, E_h and E_v, will vary from case to case since ϵ_h and ϵ_v are not necessarily constant and in the analysis they have been nondimensionalized using U_0 and H_0, which depend on discharge conditions. When accurate values for these coefficients can be determined, they should be used. In this work they were back calculated based on a best fit with data. The values so determined were assumed to be representative of the mean and taken as constant.

The data used to determine the effects of ambient turbulence on plume behavior is provided by Weil [2, 8]. In his experiments, Weil injected heated water at the surface in a turbulent channel from a semicircular jet at a relatively large densimetric jet Froude number. The discharge was in the direction of the channel current ($\theta_0 = 0$). The jet velocity in all his experiments was held equal to the local channel flow velocity. Since the relative velocity between the plume and ambient water is zero and since buoyancy effects are small due to a high Froude number, dilution is largely due to turbulence effects.

For the conditions of this experiment, the following simplifications can be introduced in the mathematical model: (*a*) Terms containing entrainment coefficient E_0 can be set equal to zero because there is no relative velocity between the jet and the ambient water. (*b*) For the same reason, the terms containing the shear coefficient, C_F, also can be set equal to zero. (*c*) The drag coefficient, C_D, is zero because the jet is parallel to the ambient current and the pressure distributions on the left- and right-hand sides of the plume are identical. (*d*) Because the heat loss in the experiments was small, one can choose a typical value of $K = 10^{-5}$ without greatly affecting the calculated plume characteristics. (*e*) Since the jet densimetric Froude number is high, the influence of the buoyant forces on the plume spread is not substantial. The plume width grows predominantly due to turbulent entrainment of the ambient water, a mechanism which the analysis accounts for through E_h and E_v. It was found that the best computer fit was obtained when $E_h = 0.02$, $E_v/E_h = 0.2$, and $C_s = 1.4$.

Entrainment Coefficient, E_0. The next group of data consists of information from several sets of laboratory and some field experiments for a surface discharge in zero or negligibly small cross current.

For the conditions of this group, one can assume that the drag coefficient is zero. As a first approximation we also assume that the contribution of the ambient turbulence is accounted for by the previously assigned values of E_h and E_v.

The best fit of the computer model with the data for this case was obtained with $E_0 = 0.05$. Since the shear coefficient had negligible effect on the result, it was set equal to zero.

Fig. 2 is a plot of the reduced temperature data from several sources where the ambient velocity was zero or negligible. Also shown are the mean and standard deviation of the data along with a computer prediction using input variables comparable to the mean experimental values. Fig. 3 is the same for plume width. It is seen that the computer prediction agrees very well with the mean of the data.

Drag Coefficient, C_D. For given values of discharge angle, Froude number, aspect ratio, and ambient current, the plume trajectory is mainly influenced by the entrainment of ambient fluid with a minor influence due to pressure drag. Since the entrainment coefficient is prespecified from the above, only the drag coefficient can be used to further adjust the trajectory. Consequently, trajectory data were regrouped for a reasonably wide range of all plume parameters mentioned above.

The best value of C_D was found to be 1.0. Fig. 4 gives reduced trajectory data from a large number of sources. Also shown are the mean and standard deviation of the data along with a computer prediction of trajectory for the mean input variables of the data.

In order to complete the adjustment of the model to fit the data, we need to check the model against measured plume width and temperature for a wide range of parameters. If agreement is obtained with such data without the need to readjust the previously specified coefficients E_0, E_h, E_v, C_F and C_D, then the fitting of the model with data is considered complete.

The raw data and calculated values based on previous coefficients are compared in Fig. 5 for plume width and in Fig. 6 for plume temperature. The agreement obtained from the comparison of calculated and measured plume width is excellent, and the agreement for plume temperature is reasonably good.

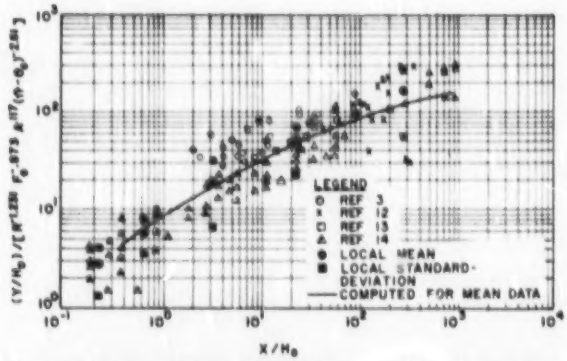

Fig. 4 Correlation of selected field and laboratory plume trajectory data as compared to calculated values

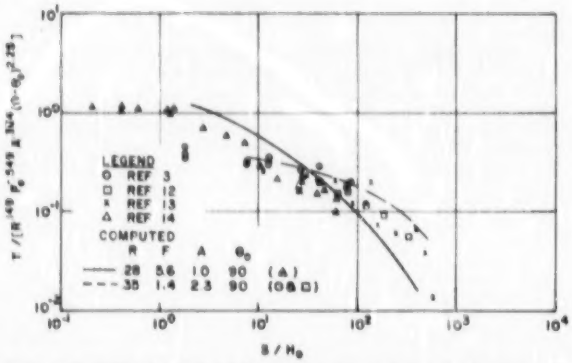

Fig. 6 Correlation of selected field and laboratory surface plume temperature as compared to calculated values

Discussion

A notable degree of data scatter could not be avoided when attempting to correlate information on plume characteristics from several sources. Physical factors not included in the data analysis but which are believed to have contributed to the data scatter are: (*a*) the lack of a universal simple exponential correlation such as used in this report; (*b*) the influence of diverse turbulence scales; (*c*) the influence of surface heat transfer; (*d*) time-dependency and boundary effects, and (*e*) instrumentation and experimental errors.

The exponential correlations employed are intended for data presentation in a compact form within each data grouping. They are not used to explain the physics of the problem exclusive of the mathematical model. They do, however, provide a statistical presentation of the level of data scatter one can expect when dealing with data from numerous sources.

There are at least two reasons why data from more than one source should be used. These are: (1) there exists no single set of data that covers a sufficiently wide range of parameters relating to initial jet conditions and ambient current; (2) data obtained for a wide range of ambient turbulence levels are reported in the literature. While the ambient turbulence level and turbulence scale affect the plume characteristics, information on these parameters is lacking in nearly all the data reported. It is felt, therefore, that a plume analysis based on several sources carries a greater degree of realism than one based on a single source.

It should be noted that the turbulence exchange coefficients in the model were back-calculated based on the best fit with the data. The coefficients are entered in a form of a turbulent Reynolds number ϵ/U_0H_0. In this manner, even though diffusivities are not directly measured in each experiment, the use of the model does provide an indirectly calculated value for the correlation parameters that best represent the available data. If in a given application, one has a better knowledge of these or any other coefficients entering the model, then of course, those should be used in the model instead.

The final conclusion is that the model can be tuned to satisfactorily predict buoyant surface jet characteristics including trajectory, width, and temperature. A set of nomograms obtained from the final tuned model for a wide range of discharge and environmental conditions is found in [11].

Reference [9], which was published after the foregoing model became available and widely used, presents an exhaustive state of the art review, critique, and assessment of the available surface jet models. As a common criterion for such assessment, the authors utilized one of the most comprehensive but recently obtained large scale field data from conventional power plant thermal outfalls. Among the analyses using the integral approach, the present model was shown to be superior in comparison with others. It was also shown, however, that much work needs to be done to obtain a truly accurate surface plume model that includes the effects of topography, wind, ambient stratification, etc.

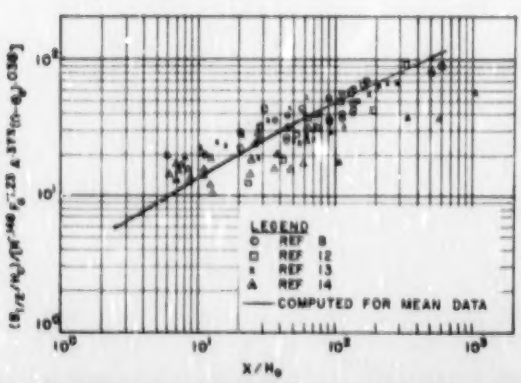

Fig. 5 Correlation of selected field and laboratory width data as compared to calculated values

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